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ORIGINAL PAPER

Radiographic quantification of dynamic hip screw migration

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Abstract

Purpose This study aimed to propose a technique to quantify dynamic hip screw (DHS®) migration on serial anteroposterior (AP) radiographs by accounting for femoral rotation and flexion.

Methods Femoral rotation and flexion were estimated using radiographic projections of the DHS® plate thickness and length, respectively. The method accuracy was evaluated using a synthetic femur fixed with a DHS® and positioned at pre-defined rotation and flexion settings. Standardised measurements of DHS® migration were trigonometrically adjusted for femoral rotation and flexion, and compared with unadjusted estimates in 34 patients.

Results The mean difference between the estimated and true femoral rotation and flexion values was 1.3° (95 % CI 0.9–1.7°) and −3.0° (95 % CI – 4.2° to −1.9°), respectively. Adjusted measurements of DHS® migration were significantly larger than unadjusted measurements ($p = 0.045$).

Conclusion The presented method allows quantification of DHS® migration with adequate bias correction due to femoral rotation and flexion.

Keywords Dynamic hip screw · Migration · Hip fracture · Radiographic quantification

Introduction

The prevalence of proximal femoral fractures is dramatically increasing in our aging population [1, 2]. Even with the advent of new implant technologies, particularly stable fractures, pertrochanteric fractures and femoral neck fractures are still commonly fixed with the dynamic hip screw (DHS®) [3]. Yet fixation of such fractures is becoming more challenging because the majority of these fractures now occur in osteoporotic bone with low biomechanical competence [4]. High complication rates have been reported after the fixation of proximal femoral fractures [5–9]. The hip screw may migrate cranially within the femoral head as a consequence of a secondary displacement of the head–neck fragment into a varus position. In 2.5–16 % of cases, the hip screw may ultimately “cut out”, i.e. penetrate the femoral head in its superior part [9–15]. Early detection of DHS® migration is important to reduce patient morbidity. In such cases, postoperative rehabilitation may be modified accordingly until complete fracture healing.

The detection of cranial DHS® migration is based on serial measurement of the distance between the DHS® tip and an anatomical landmark of the femoral head. Although this distance is three-dimensional in nature, it is usually assessed on two-dimensional radiographs. Therefore, the accuracy of these measurements depends on the appropriate and consistent positioning of the proximal femur at the time of radiography. For unbiased measurements, the direction of the radiographic beam must be perpendicular to the plane of the DHS® implant, i.e., perpendicular to the femoral neck and shaft axis if the implant is correctly placed into the proximal femur. Thus, every change in hip rotation and flexion on consecutive AP views can simulate mediolateral and vertical screw migration, respectively [16].

Laurent Audigé and Flurin Cagienard equally contributed to this work and share first authorship.

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During postoperative follow-up radiography, patients are often unable to adopt the required leg position relative to the X-ray plane because of residual pain. Consequently, the assessment of postoperative cranial screw migration becomes difficult even for the experienced clinician; clinical judgment would benefit from the support of a standardised measurement technique. Therefore, the goal of this study was to develop and validate a new method to quantify cranial DHS® migration following the fixation of proximal femoral fractures using standard radiographs with adjustments made for hip rotation and flexion.

Materials and methods

Study design

The study design comprised three stages: (1) the development of mathematical formulae to estimate femoral rotation and flexion relative to the X-ray plane and to adjust for measurements of DHS® migration to known values of femoral rotation and flexion, (2) the determination of accuracy of rotation and flexion angle estimates in an experimental setting, and (3) the proof-of-concept and clinical applicability of the method using retrospective patient data.

Estimation of femoral rotation and flexion

The method to estimate femoral rotation and flexion relative to the X-ray plane on plain radiographs was based on the consideration that measurements of known implant dimensions perpendicular to the DHS® plate length axis (hereafter referred to as "horizontal") change with femoral rotation, while measurements of known implant dimensions in the plate length axis (hereafter referred to as "vertical") change with femoral flexion. Therefore, measurements of known horizontal and vertical implant dimensions—which are corrected for magnification—can be used to estimate the femoral rotation and flexion angle relative to the X-ray plane, respectively.

Alignment of the radiographic measurements axis according to the plate length axis

In order to align radiographic measurements according to the plate length axis, a coordinate system centred at the "plate barrel axis" (Pba point), i.e., the intersection between the mid-axes of the plate and barrel was applied (Fig. 1). All point coordinates were transformed using trigonometric formulae so the plate middle axis and thus all Y coordinates are presented in a vertical manner, while X coordinates are presented horizontally.

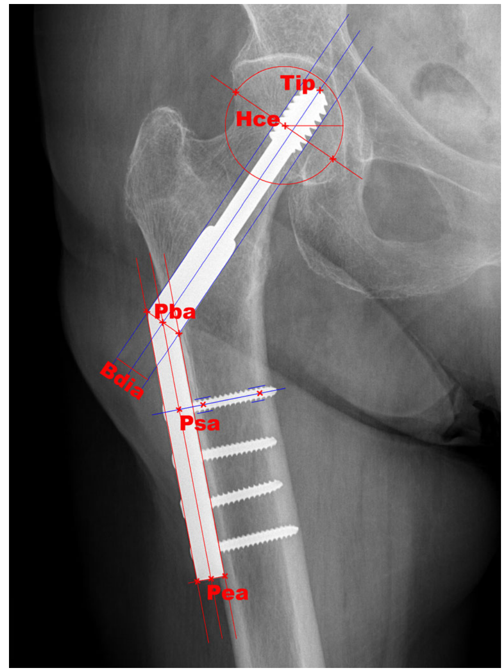

Fig. 1 Radiographic landmark points on anteroposterior (AP) view. Tip DHS® tip, Hce head centre, Pba plate barrel axis, Bdia barrel diameter, Psa plate screw axis, Pea plate end axis

Correction of the radiographic measurements for magnification

All measurements and landmark point X/Y coordinates were adjusted for magnification using the formula below, which considers the measured DHS® barrel diameter (Bdia) value (Fig. 1) that is not affected by femoral rotation and flexion and its true equivalent equal to 12.6 mm.

$$Adjusted\ \ distance\ (mm) = \frac{Raw\ distance\ (pixel)}{Raw\ DHS\ barrel\ diameter\ (pixel)} \times\ 12.6\ mm \qquad (1)$$

Determination of femoral rotation (α) and flexion angle (β) relative to the X-ray plane

The femoral rotation angle (α) was estimated using the projected thickness of the DHS® plate. After correction for magnification, this measurement is equal to the plate thickness if no femoral rotation occurs and increases otherwise. The relationship between projected plate thickness and α is described by two sets of formulae in relation to a femoral rotation threshold rotation angle of 18°, which considers plate curvature (Appendix). A table of values relating α to the plate thickness projection was constructed to provide a rotation angle estimate for any measured plate thickness (Fig. 2a) (Online Resource 2).

The projected distance (Lproj) between the Pba and Psa point ("plate screw axis"=the intersection point between the

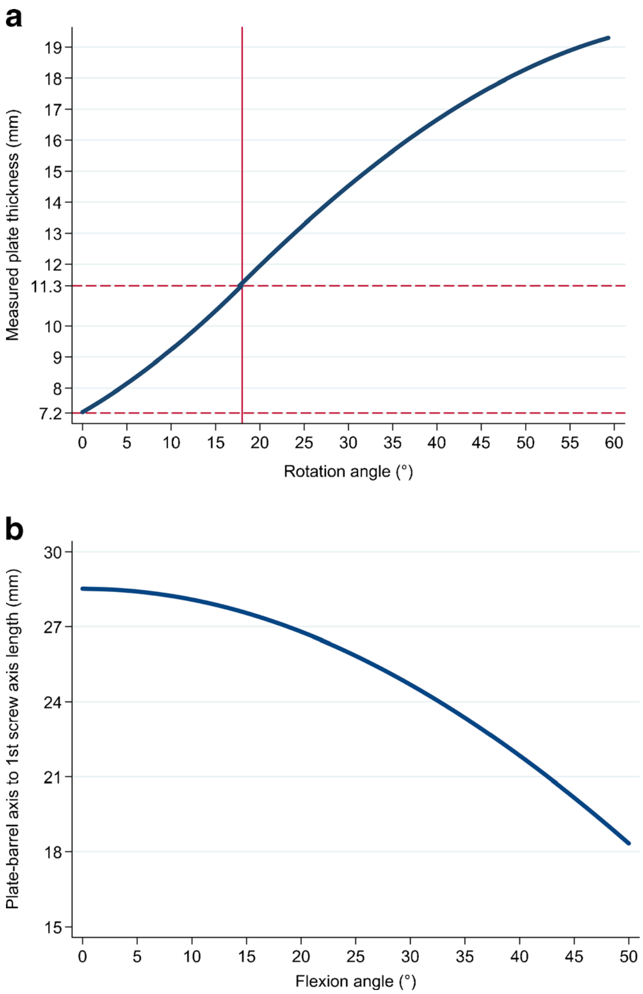

Fig. 2 **a** Relationship between DHS® plate width projection and the femoral rotation angle. **b** Relationship between plate axis-first screw axis length projection and femoral flexion angle

mid-axis of the plate) (Fig. 1) was used to estimate the femoral flexion angle (β). As femoral flexion increases, Lproj becomes smaller than the true value L=28 mm (Fig. 2b).

$$\text{Femoral flexion } \beta \text{ (degree)} = \arccos\left(\frac{L_{proj}}{L}\right) \times \frac{180}{\pi} \quad (2)$$

Quantification of cranial DHS® migration in plain radiographs with regard to hip rotation and flexion

In order to calculate cranial screw migration between two time points, the coordinate system was transformed with its origin in the centre of the femoral head (landmark point: Hce=head center) (Fig. 1). The X/Y coordinates of the screw tip (landmark point: Tip) were determined on each postoperative (post-OP) and follow-up (FU) radiograph. DHS® migration was calculated according to the Pythagorean theorem in as shown in Online Resource 1.

$$\mathbf{DHS^{®}\ migration(mm)} = \sqrt{\left(\boldsymbol{Tip}_{X\ (\mathrm{Post-OP})} - \boldsymbol{Tip}_{X\ (\mathrm{FU})}\right)^2 + \left(\boldsymbol{Tip}_{Y\ (\mathrm{Post-OP})} - \boldsymbol{Tip}_{Y\ (\mathrm{FU})}\right)^2} \quad (3)$$

Adjustment of DHS® migration for femoral rotation and flexion

Specifically for each radiograph, all X-axis coordinates used in the formulae were adjusted for hip rotation, and Y-axis coordinates were adjusted for hip flexion using the following trigonometric formulae:

$$\text{Adjusted X coordinate} = \frac{\text{X coordinate}}{\cos\left(\text{rotation angle } \alpha \times \frac{\pi}{180}\right)} \quad (4)$$

$$\text{Adjusted Y coordinate} = \frac{\text{Y coordinate}}{\cos\left(\text{flexion angle } \beta \times \frac{\pi}{180}\right)} \quad (5)$$

Experimental validation of rotation and flexion estimations

In order to assess the accuracy of femoral flexion and rotation estimates, a synthetic model of a proximal femur (Synbone, Malans, Switzerland) was fixed with a four-hole square-ended 135° DHS® (Synthes, Oberdorf, Switzerland) . A series of standardised AP radiographs were taken at combined angles of DHS® plate (i.e. femoral) rotation (0°, 5°, 10°, 15°, 20°, 25°, 30°, 35° and 40°) and flexion (0°, 10°, 20°, 30° and 40°) relative to the X-ray plane. Duplicate radiographs were taken for rotation values of≤20°. Digital radiographs were analysed by a blinded observer (FC) using the software Axiovision 4.5 (Carl Zeiss MicroImaging GmbH, Jena, Germany). Measurements and landmark point co-ordinates were transformed as previously described to derive the rotation and flexion angles.

Clinical evaluation

Patient demographics

Thirty-four patients were retrospectively included in a clinical evaluation study. The patient population comprised 23 females and 11 males with a mean age of 68 years (range, 37–97 years) who sustained 17 femoral neck (Müller-AO: 9 B1, 4 B2, 4 B3) and 17 pertrochanteric fractures (13 A1, 4 A2) which were fixed with the 135° DHS®.

Radiographic measurements

Immediate postoperative and three-month follow-up digital AP and lateral radiographs from each patient were collected and anonymised. Radiographs were independently reviewed by a board-certified (MAM) and resident orthopaedic surgeon (FC) to classify each patient according to the three categories of DHS® migration: "clearly stable" (no noticeable movement), "possibly migrated" (neither stable nor migrated), "clearly migrated" (clinically visible migration, but no cut-out). Coding disagreements were resolved by consensus. Radiographs were analysed by the one of the authors (FC) to record the landmark coordinates using the software Axiovision 4.5. Screw migration values were calculated by comparing immediate postoperative and three-month follow-up radiographs, with and without adjustment for estimated femoral flexion and rotation relative to the X-ray plane as previously described and shown in detail in Online Resource 1.

Statistical analyses

The concordance coefficient [17] between estimated and experimental values was calculated. Unadjusted and adjusted measurements of DHS® migration were compared using the Wilcoxon signed-rank test. Screw migration was separately compared among the three clinical consensus categories using the Kruskal-Wallis rank test. Analyses were conducted with the software Intercooled Stata version 11 (StataCorp LP, Texas, USA). The significance level was set at 0.05.

Results

Experimental validation of rotation and flexion estimations

The mean difference between the estimated and true rotation values was 1.3° (95 % CI 0.9–1.7°). The concordance coefficient between the two values was 0.984. There was a linear relationship between estimated and true rotation values (R^2= 0.99, Fig. 3a). There was a significant effect of hip flexion on the rotation estimates; the estimated rotation increased with every 10° increase in flexion ($p<0.001$).

The mean difference between the estimated and true flexion values was −3.0° (95 % CI −4.2° to −1.9°) with a concordance coefficient of 0.912. The estimated value showed more variability for cases with a flexion range up to 20°. The relationship between the estimated and true flexion values was fitted with a quadratic function (R^2=0.96, Fig. 3b) and was not related to femoral rotation (p=0.16).

Clinical evaluation

The consensus agreement identified 23 cases with "no migration", six cases with "possible migration", and five patients with "clear migration". Mean values for unadjusted and flexion/rotation-adjusted screw migration measurements

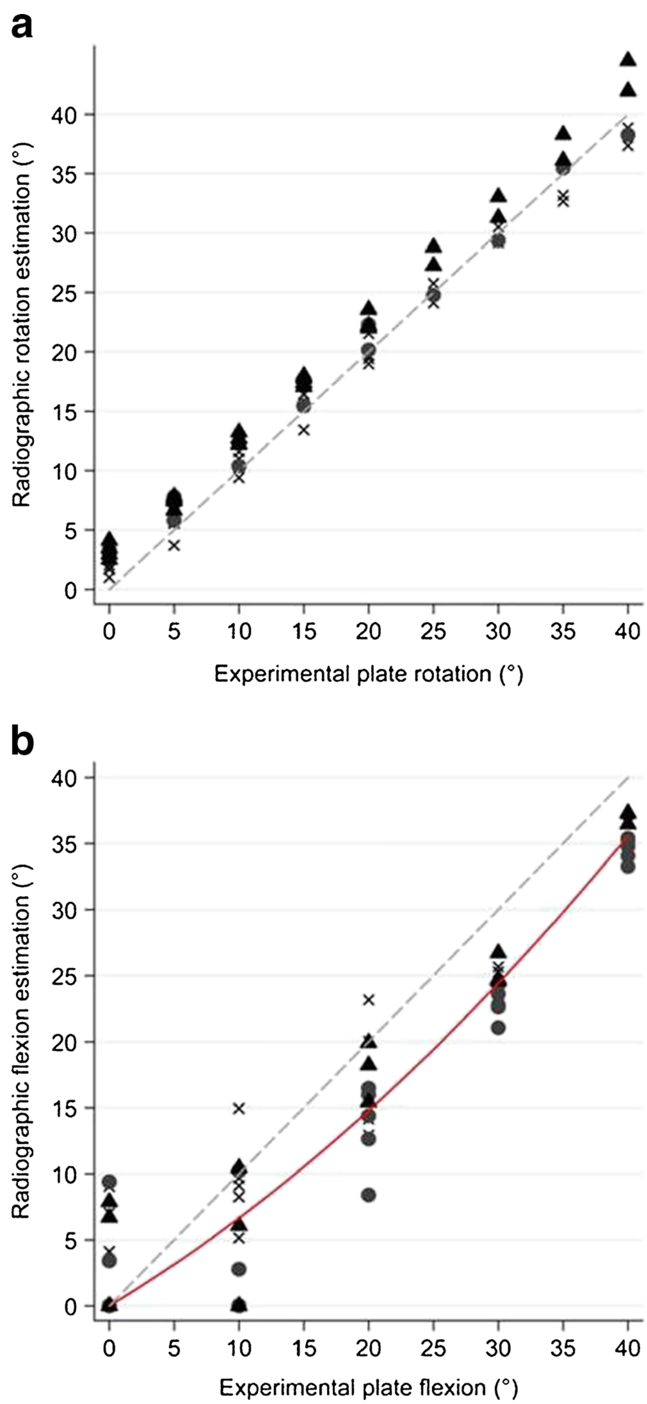

Fig. 3 Relationship between experimental and estimated femoral plate rotation (**a**) and flexion (**b**) angles. **a** Crossed, circular and triangular data points were collected at 0°– 10°, 20° and 30°– 40° of experimental femoral plate flexion, respectively. **b** Crossed, circular and triangular data points were collected at 0°– 10°, 15–25° and 30°– 40° of experimental femoral plate rotation, respectively

showed significant increases for patients identified with "clear migration" ($p<0.01$). For all groups, adjusted radiographic measurements of screw migration were significantly larger than the unadjusted measurements (range, −2.1 – 3.2; p=0.045) (Table 1).

Table 1 Differences between measurements of DHS migration either adjusted or unadjusted for hip rotation/flexion for each group of the clinical evaluation study

Group according to clinical judgment	DHS® migration adjusted for hip flexion/ rotation (mm)		DHS® migration unadjusted for hip flexion/rotation (mm)		Sign rank test P- value
	Median	Range	Median	Range	
"Clearly stable" (n=23)	0.9	0.2–2.8	0.6	0.0–3.2	0.07
"Possibly migrated" (n=6)	1.1	0.6–3.7	1.0	0.1–2.3	0.35
"Clearly migrated" (n=5)	3.5	2.3–10.7	4.4	1.7–7.5	0.69
Kruskal-Wallis rank test P-value	0.003		0.003		

In the "no migration" and "possible migration" groups, large differences between unadjusted and adjusted estimates of DHS® migration were observed if the true screw displacement and/or differences in the total rotation/flexion estimates were large (Fig. 4).

In contrast, in the "clear migration" group even a large difference in the rotation/flexion angle could create a small difference between adjusted and unadjusted values if screw migration was mainly in the vertical direction and if radiographs mainly differed in femoral rotation (patient 26). Large differences between adjusted and unadjusted screw migration were observed despite similar total rotation/flexion angles if femoral rotation and flexion was pronounced (> 35°) at both time points (patient 25).

Discussion

The goal of this study was to develop and validate a novel technique to quantify cranial DHS® migration from AP radiographs, independent of femoral rotation and flexion relative to the X-ray plane. Early radiographic detection of DHS® migration is important to prevent serious complications, but remains a challenging endeavour. We developed a mathematical algorithm to estimate femoral rotation and flexion from measured radiographic AP projections of the DHS® plate thickness and proximal length to the first screw hole, respectively, after correction for the radiographic beam magnification.

In ex-vivo evaluation, our technique was highly accurate for the estimation of femoral rotation, although there was a minor but significant distortive effect of femoral flexion on these estimates. With concordance correlation coefficients above 0.90 and mean differences with true values of 2–3°, these estimates can be considered reasonably accurate for the purpose of adjusting radiographic measurements with regards to imperfect patient positioning. For the quantification of femoral flexion, increased variability was noted particularly in the lower scale from 0 to 20°. The measurement variability is related to factors common to both unadjusted and adjusted measurements such as radiograph acquisition and patient position [18, 19]. The identification of radiographic landmarks adds variability for adjusted measurements [18]. Nevertheless, our aim was to obtain adequate estimates of hip rotation and flexion in order to account for severe deviations from ideal hip positioning, and not to achieve perfect estimation accuracy.

As demonstrated by our study, unadjusted measurements of DHS® migration can be variably biased. Clinically obvious screw migration can be substantially underestimated if femoral flexion and/or rotation is large at either or both the immediate postoperative and follow-up examinations. However, if hip screw migration primarily occurs along the vertical axis, even pronounced differences in rotation may not create relevant differences between adjusted and unadjusted measurements.

The development of our technique was adapted from methods described by Gardner et al. [20, 21] and Watanabe et al. [22]. These methods had already applied

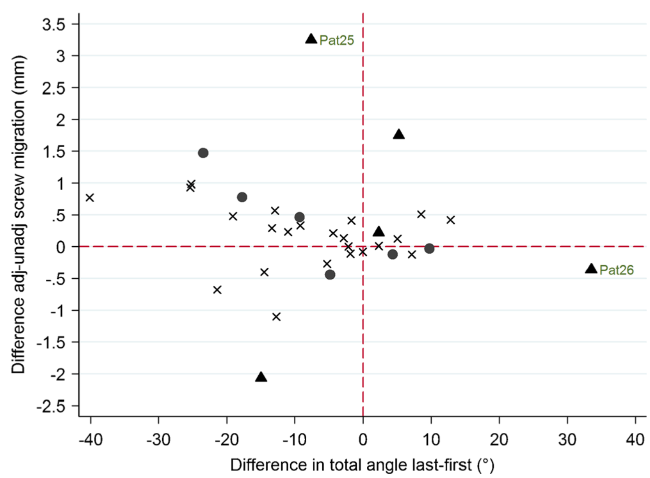

Fig. 4 Difference between adjusted and unadjusted measurements of DHS® migration as a function of the difference between total hip flexion and rotation angles estimated on the immediate postoperative and three-month radiographs. Crossed data points = "no migration" group; circle data points = "possible migration"; and triangle data points = "clear migration" group. adj-unadj difference between adjusted and unadjusted measurements, last-first difference between total angle from on the first immediate post-operative X-rays and that from the last three-month X-rays

a co-ordinate system to quantify vertical hip screw migration of intramedullary nails. The projected length of the hip screw was also used to correct measurements for hip rotation [20, 21], but measurements were not adjusted for hip flexion. Raudaschl et al. [23] proposed a CT-based technique to quantify hip screw migration of intramedullary nails independent of hip flexion and rotation. Hip screws were segmented from consecutive CT images and aligned in a CT-based coordinate system. In clinical evaluation, the technique showed a mean measurement error of 0.516 mm. This CT-based technique is capable of quantifying hip screw migration in three-dimensional space, while our technique measures hip screw migration in the plane of an AP view. Nonetheless, the application of CT techniques in the postoperative follow-up of hip fracture patients is still limited by availability, costs and additional radiation exposure.

We acknowledge several limitations of the presented technique. The projections of plate thickness and plate length in the AP view were used to quantify femoral rotation and flexion, respectively. Hence, the technique effectively quantifies the position of the DHS® implant relative to the X-ray plane, which only corresponds to the actual femoral rotation and flexion if the DHS® is implanted in a correct manner (i.e., parallel to the femoral shaft and neck axis). However, our technique defines DHS® migration as a change of the position of the screw tip related to the centre of the femoral head. The projection of the femoral head centre does not alter with flexion or rotation of the proximal femur. Therefore, measurements of DHS® migration are not distorted even if the plane of the DHS® implant does not perfectly overlap with the plane of the proximal femur.

From our experience, the analysis of each radiograph took an average 12 minutes. The presented technique may therefore be applied in clinical cases where screw migration is suspected but is still inconclusive on a plain radiograph. The technique may also be useful in clinical research for investigating the effectiveness of implants designed for hip fracture fixation in osteoporotic bone. Although this technique has been developed exclusively for the DHS®, our approach can be adopted for other implants. In such studies [24], the incidence of cut out is often considered as the primary outcome; it is, however, a dichotomous parameter requiring large sample sizes for adequate study power. With our technique, cut out could be replaced by screw migration as a continuous and ethically favourable primary outcome.

In conclusion, we have developed and validated a novel technique to quantify DHS® migration independent of hip flexion and rotation relative to the X-ray plane. The technique may allow one to take preventive measures against DHS® cut out in a timely manner. In clinical research, this method provides a new outcome measure to assess the effectiveness of new fixation techniques designed for osteoporotic bone.

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Conflict of Interest The authors declare that they have no conflict of interest.

Appendix : Detailed presentation of formulae to estimate femoral rotation angle

The relationship between the projected thickness of the DHS® plate (T_{proj}) and the femoral rotation angle (α) is described by two sets of formulae (Fig. 5):

Above a femoral rotation threshold angle of 18°, the DHS® plate curvature radius (C) does not influence the relationship between T_{proj} and α. Femoral rotation is then calculated as follows (Fig. 5b) :

$$\text{Femoral rotation } \alpha \text{ (degree)} = 90 - \alpha_1 - \alpha_2 \tag{6}$$

$$\alpha_1(\text{degree}) = \arctan\left(\frac{T_2}{W}\right) \times \frac{180}{\pi} \tag{7}$$

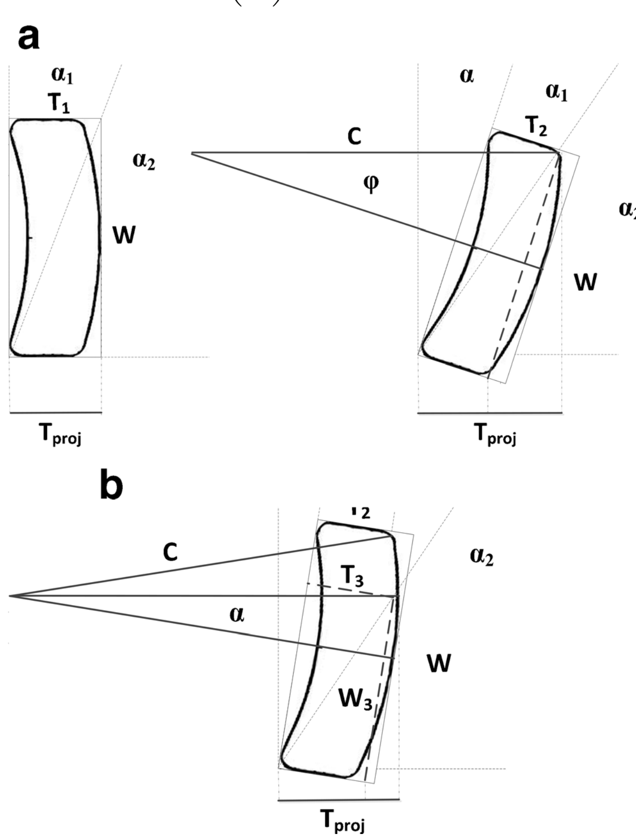

Fig. 5 Representation of DHS® plate projection (Tproj) with and without rotation. Abbreviations: T=true plate thickness (T_1=7.23 mm, T_2= 5.8 mm); W = true plate width=19 mm; C = radius of plate curvature (30.8 mm); α = rotation angle (defined as $90 - \alpha_1 - \alpha_2$); φ = threshold rotation angle, i.e., the value of rotation above which the DHS® plate curvature influences the relationship between T_{proj} and α. T_3 and W_3 define the thickness and width, respectively, of a fictive plate defined according to the rotation angle α

$$\alpha_2(\text{degree}) = \arccos\left(\frac{T_{proj}}{\sqrt{{T_2}^2 + W^2}}\right) \times \frac{180}{\pi} \tag{8}$$

For rotation angles ranging from 0 to 18°, the projection of the plate curvature must be considered. The formula presented above can be applied on a "fictive plate" defined by its width, W_3 and thickness, T_3 in relation to the rotation angle as follows (Fig. 5c):

$$\text{Rotation angle } \alpha \text{ (degree)} = 90 - \left(\arctan\frac{T_3}{W_3} + \arccos\frac{T_{proj}}{\sqrt{{T_3}^2 + {W_3}^2}}\right) \times \frac{180}{\pi} \tag{9}$$

$$W_3 = {}^{W}/_{2} + C \times \sin\propto \tag{10}$$

$$T_3 = T_1 - C\ x(1 - \cos\propto) \tag{11}$$

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